



Design Loads Prediction on Fixed Offshore Support Structures

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Design Loads Prediction on Fixed Offshore Support Structures

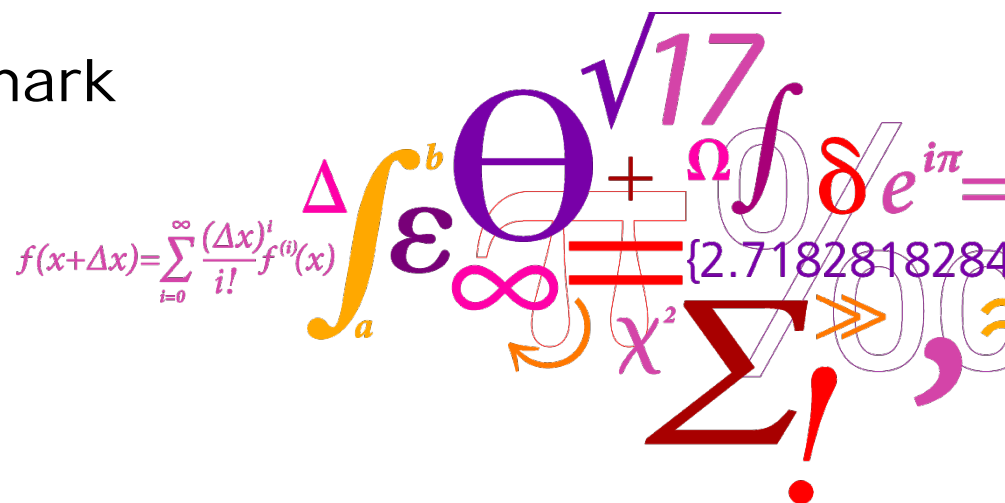
Anand Natarajan

Wind Turbine Structures

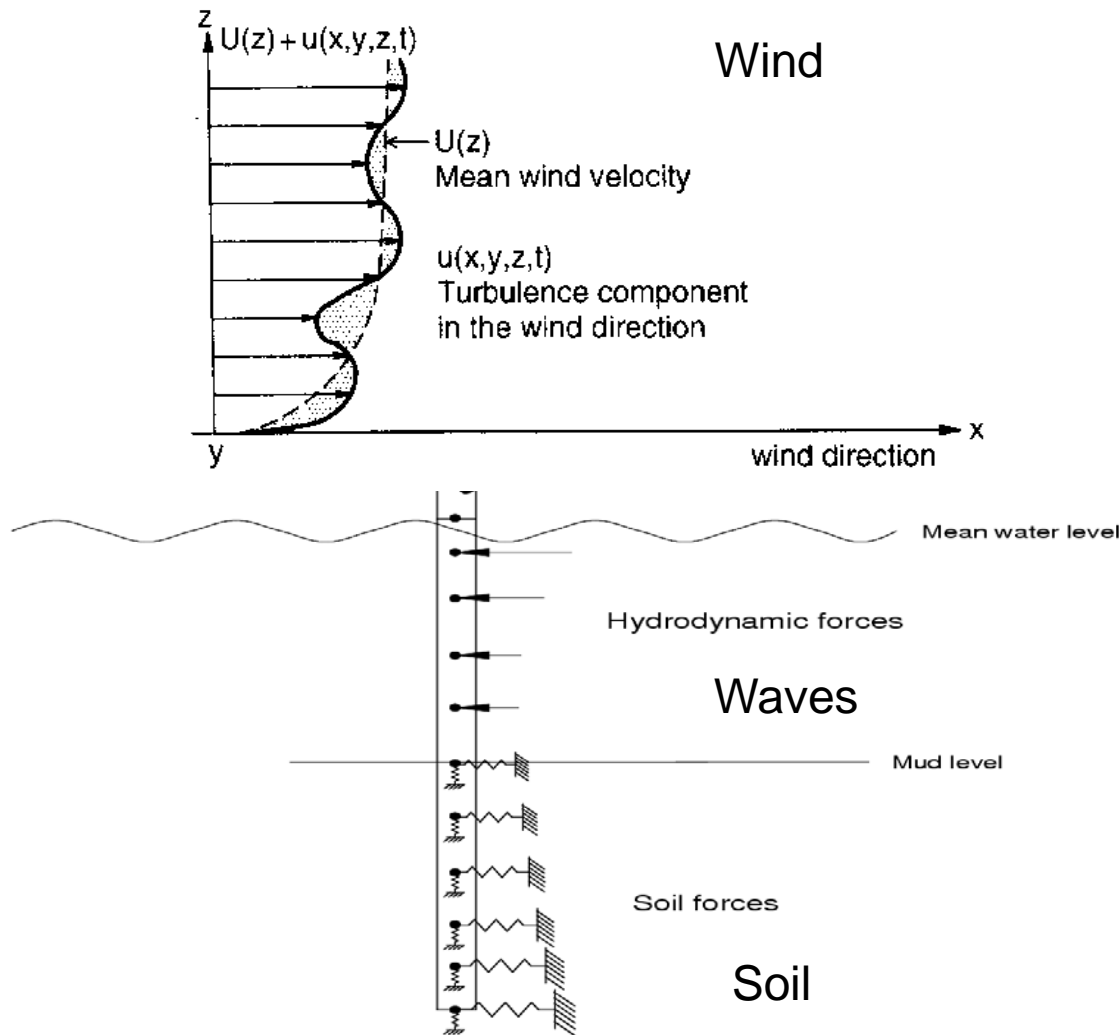
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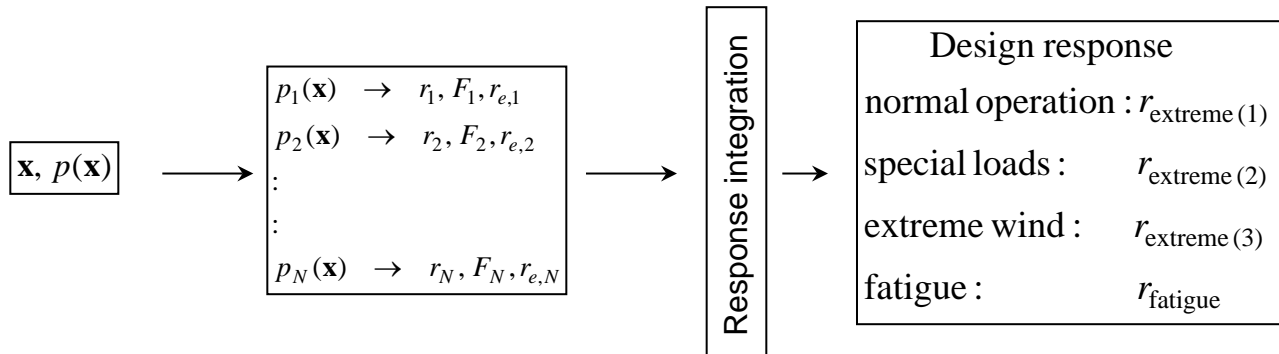
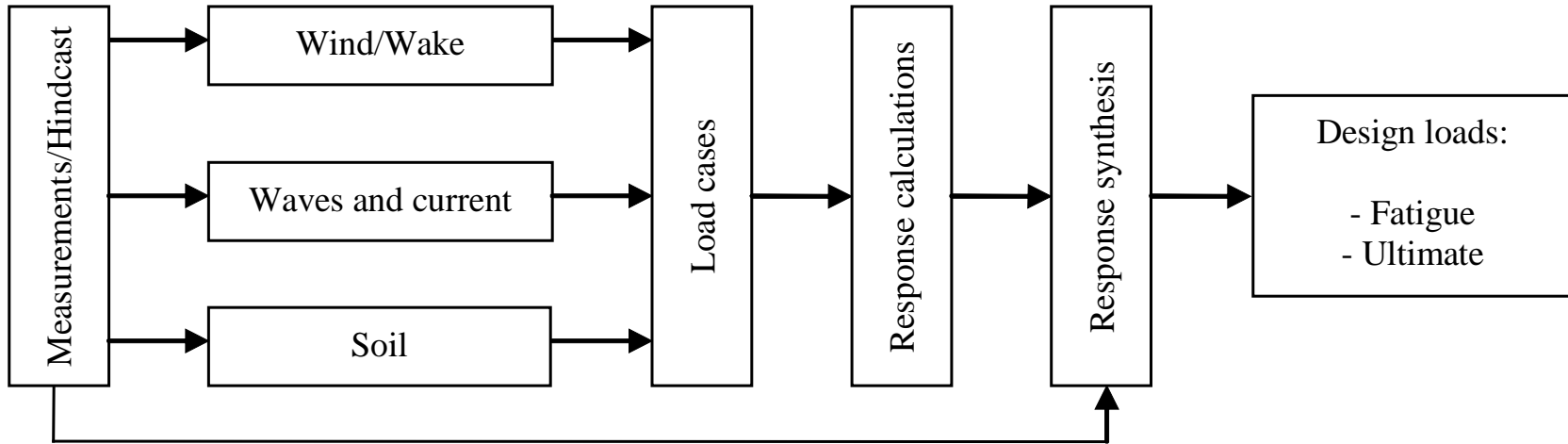


Loads on an Offshore Wind Turbines

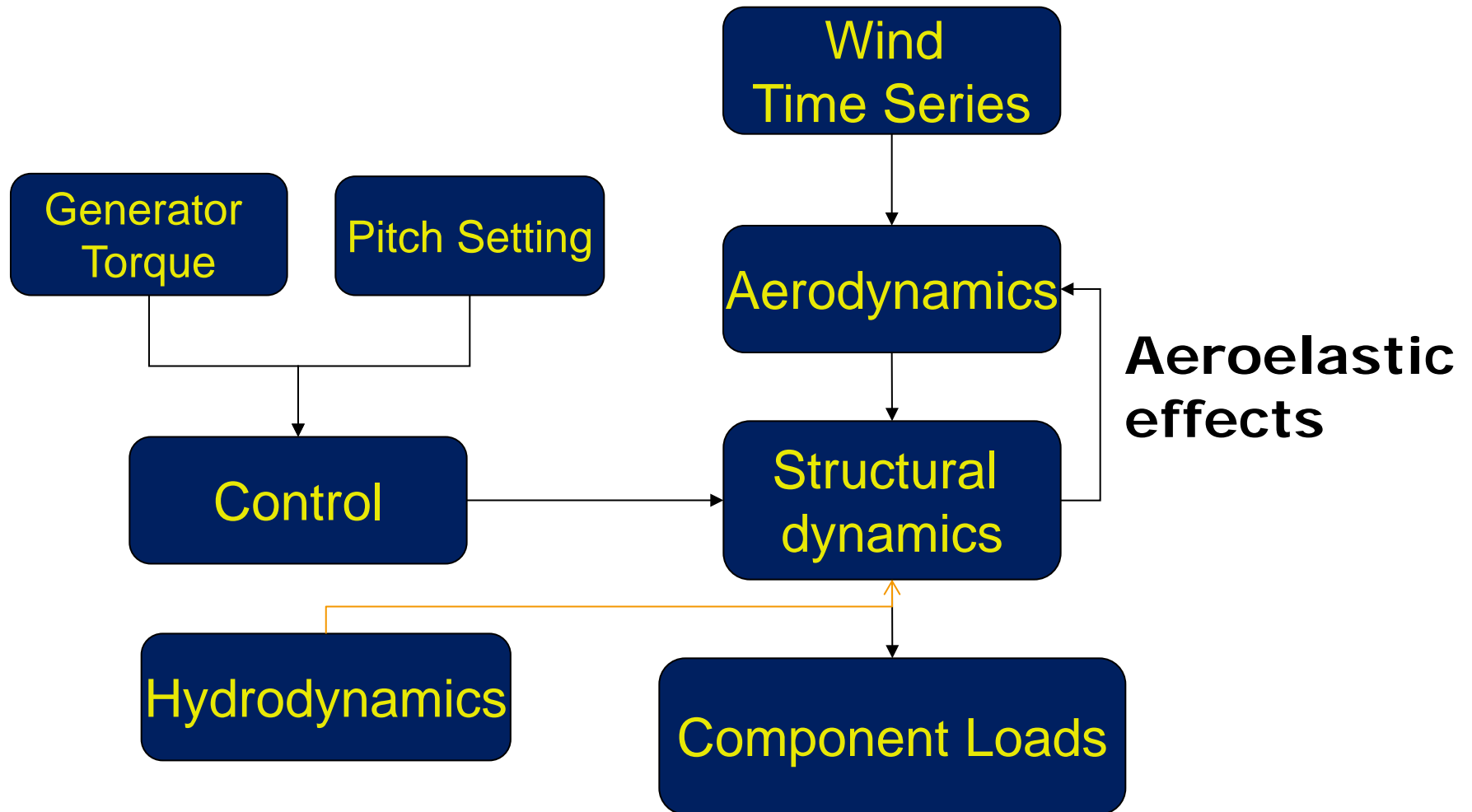


- ✓ Inertial Loads
- ✓ Aerodynamic forces on the rotor
- ✓ Aerodynamic drag on the support structure
- ✓ Hydrodynamic forces
- ✓ Forces from Soil interaction
- ✓ Ice impact or other floating object impacts

Design Load Evaluation Process

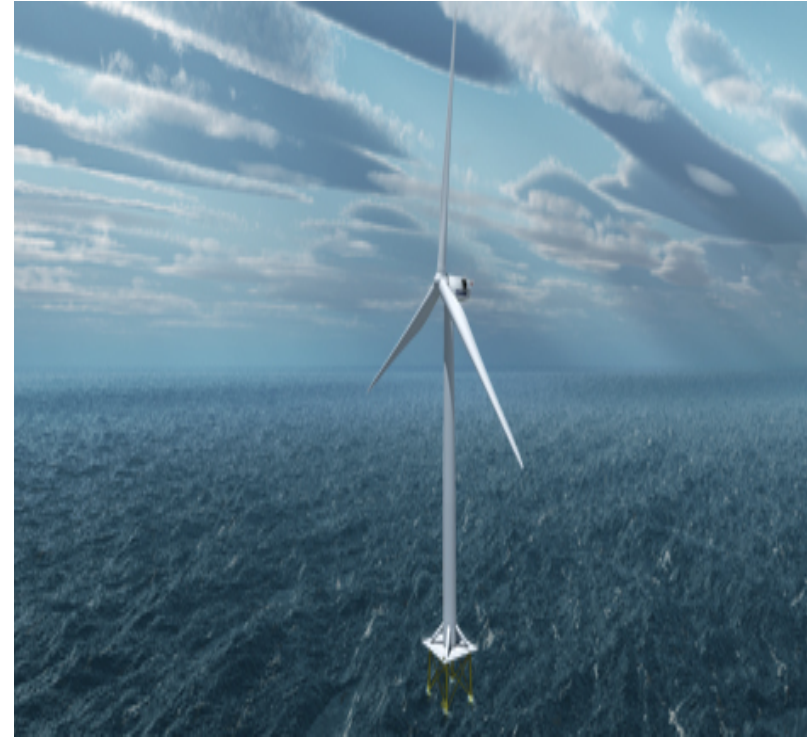


Wind Turbine Loads Simulation



Moving to 30m-50m Water Depth

- Monopile sub structures have been the most widely installed sub structure below 30m water depths.
- Many moderate water depth (<40m) installations use Jackets or tripods which can be costly.
- Can the monopile sub structure be used in deeper waters?
- Reduce sub structure design uncertainties



Vestas V164 8MW

Design Load Dependencies



- Hydrodynamic effects : The wave mechanics is nonlinear and stochastic, but most loads simulations do not treat this.
- Site specific calibrations: The impact of the soil and wave conditions is site specific
- Effects from the Rotor: The overturning moments due to rotor loads significantly impact the sub structure design.
- Coupled versus uncoupled loads simulation
- Stochastic processing of loads: Loads simulations are done over a few days of turbine lifetime and extended to
- Extreme loads versus Fatigue loads : The long term estimation of these quantities can have significant uncertainties.

Hydrodynamic models for loads prediction in deeper waters

Conventional approach	Proposed Approach
Airy linear wave kinematics	Nonlinear random wave kinematics
Prescribed wave spectra	Site specific spectral analysis
Waves aligned with the wind	Wind/wave misalignment
10 minute loads simulations	Much longer simulations to account for joint wind/wave statistics
Splash zone ignored or stretching methods used	Require to model the wave crest kinematics above the mean water level
Gaussian Statistics	Consider Non Gaussian Effects

Second Order Nonlinear Random Waves

- Resulting equation satisfies the free surface boundary conditions to the second order (Unsteady Bernoulli) without the need for stretching methods.
- The wave process is non Gaussian.
- The waves are skewed with uneven troughs and crests.
- The wave kinematic model allows the representation of sum and difference frequencies.

$$u_2 = \sum_{i=1}^N \sum_{j=1}^M B_j B_i [P_{ij} \cos(k_{ij}^- x - \omega_{ij}^- t + \beta_i) + Q_{ij} \cos(k_{ij}^+ x - \omega_{ij}^+ t + \beta_i)]$$

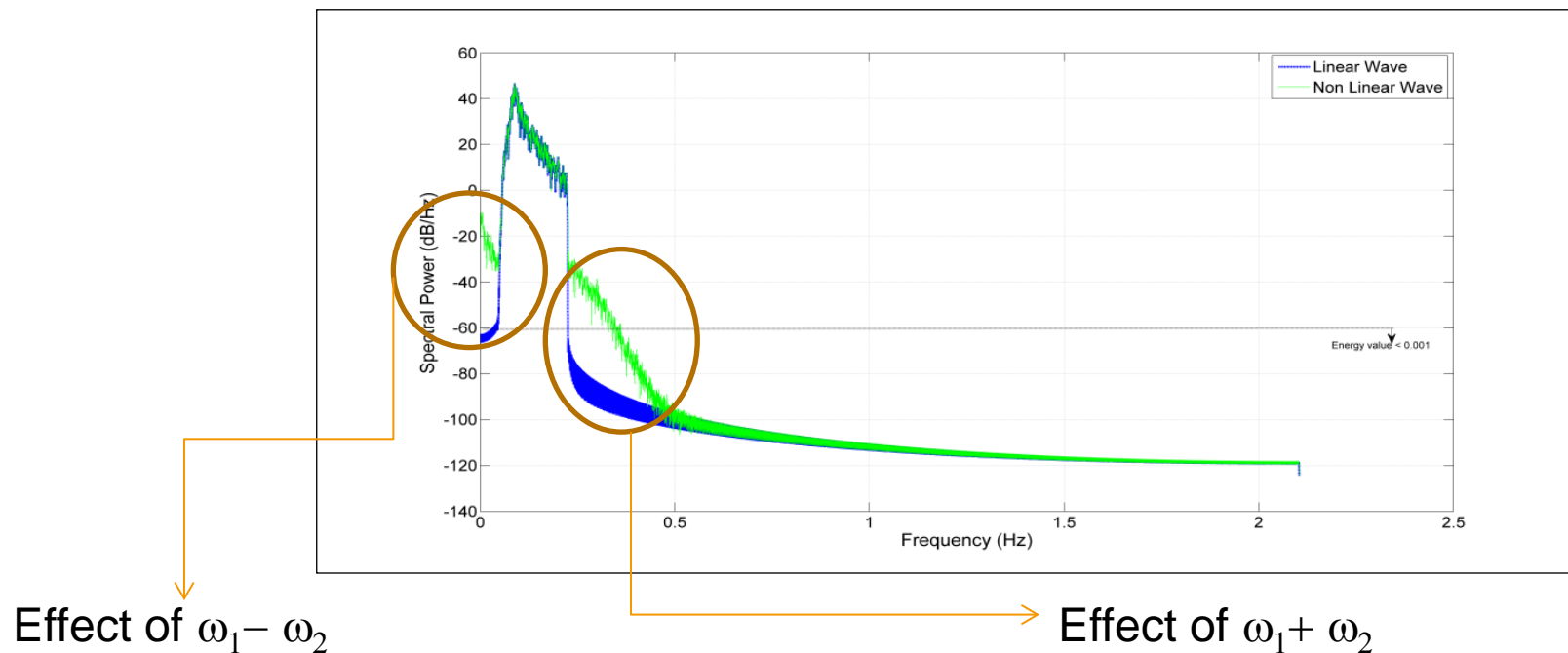
$$\dot{u}_2 = \sum_{i=1}^N \sum_{j=1}^M C_j C_i [R_{ij} \sin(k_{ij}^- x - \omega_{ij}^- t + \beta_i) + S_{ij} \sin(k_{ij}^+ x - \omega_{ij}^+ t + \beta_i)]$$

$$\omega_{ij}^- = \omega_1 - \omega_2$$

$$\omega_{ij}^+ = \omega_1 + \omega_2$$

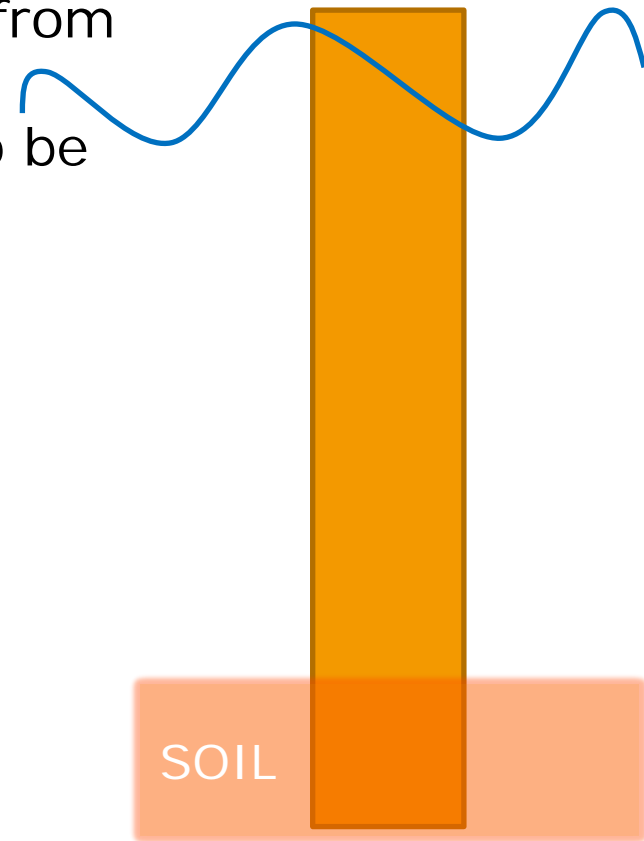
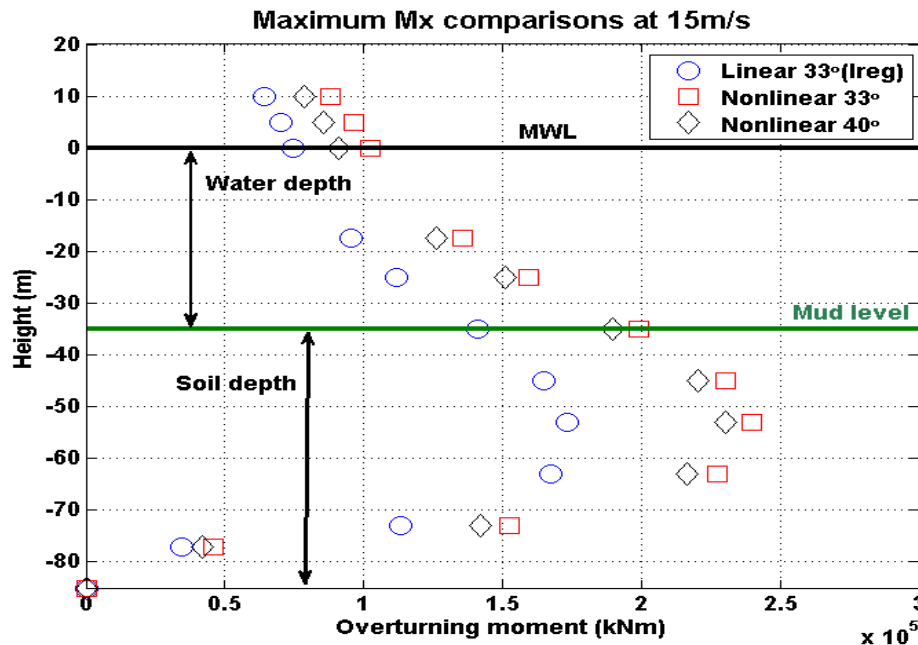
Effect of Wave Non linearity

- The effect of the wave sum frequency ($\omega_1 + \omega_2$) and difference frequency ($\omega_1 - \omega_2$) results in larger spectral bandwidth of the wave process.
- The larger bandwidth of the non linear wave PSD can interact with the support structure frequencies more in the presence of flexible soil conditions.



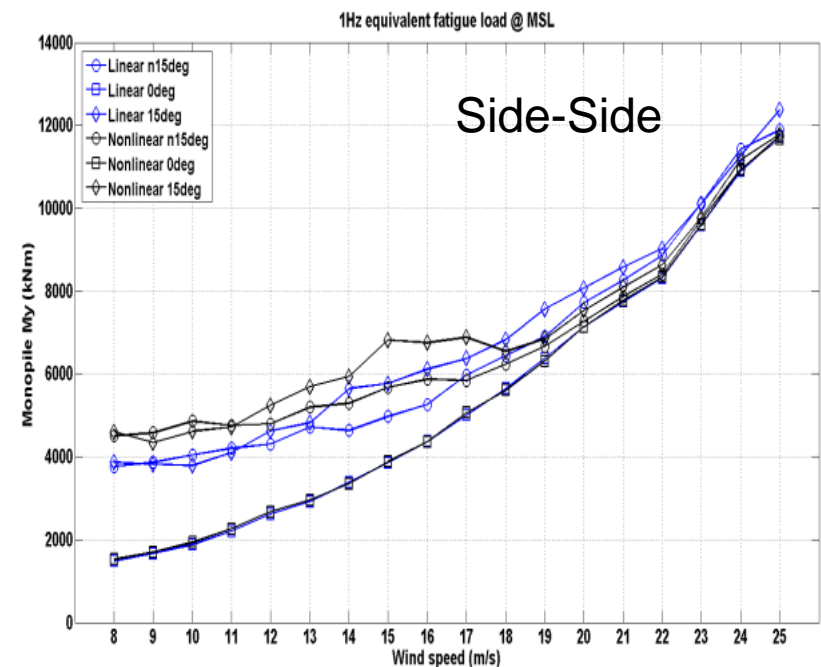
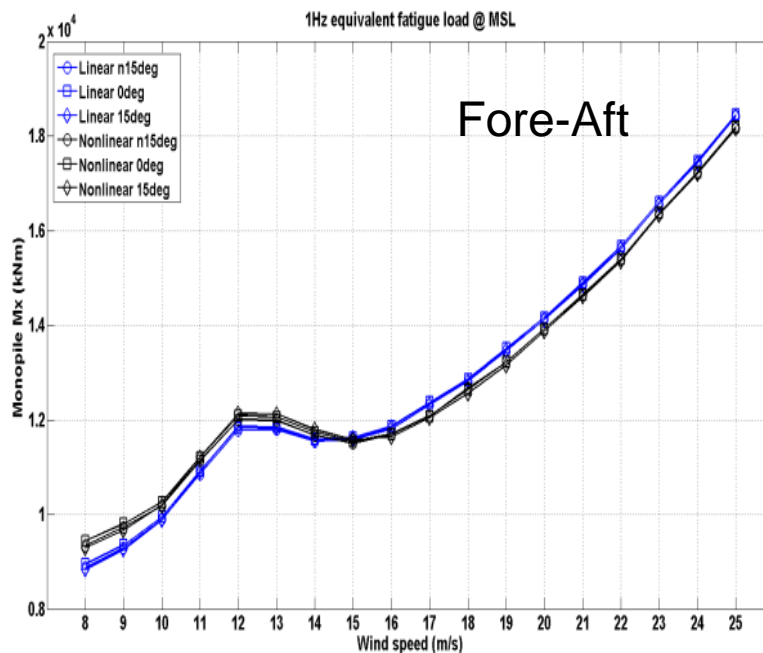
Effect of Soil Flexibility and non linear waves

- Soil flexibility is modeled as a distributed spring for a monopile situated in 35m water depth.
- Support structure frequency is decreased from 0.29 Hz to 0.23 Hz, causing the extreme mudline moment from non linear waves to be 35% greater than with linear waves.



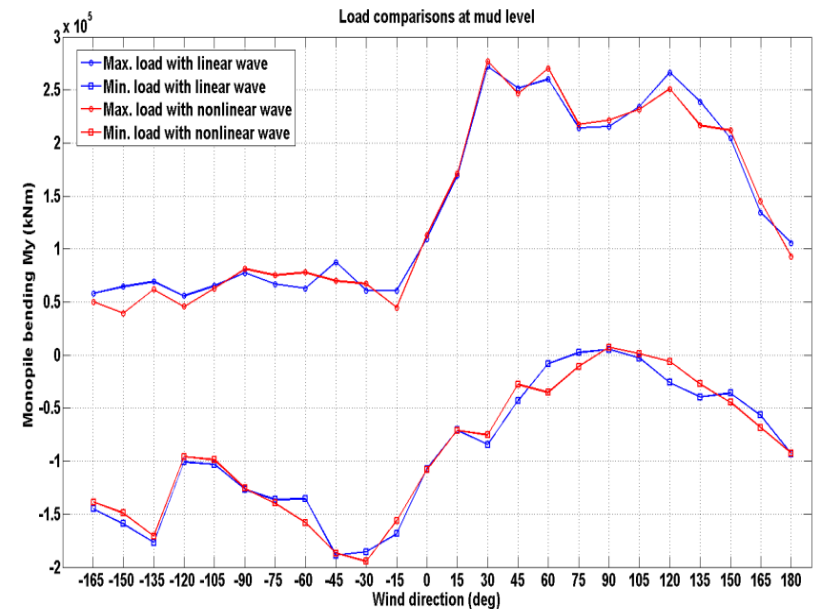
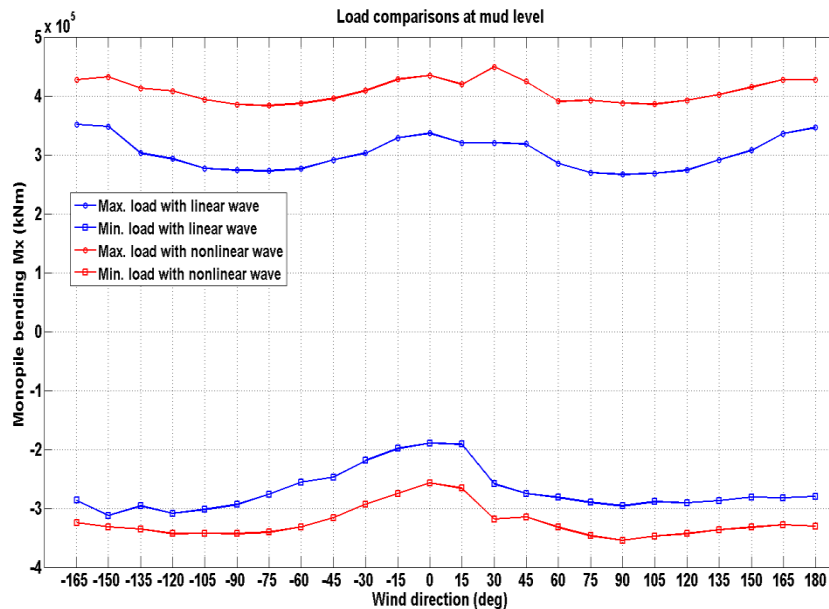
Effects of Wind/Wave Misalignments

- The 1Hz. Damage Equivalent loads over the monopile reveal that the fore-aft moment is not affected by the wave kinematic model.
- The side to side Damage Eq. moment shows a large increase in the presence of nonlinear waves below rated wind speed.
- The side to side moment is dominated by the rotor loads at higher mean wind speeds, which decides the ultimate design limit.



50 Year Storm Extreme Load-Flexible Soil conditions

- Wind/wave orientation with respect to the turbine nacelle is varied over 360° in steps of 15° .
- The nonlinear wave kinematics increases the extreme fore-aft moment (M_x) by ~ 20 - 25%
- The side to side extreme moment (M_y) is not affected by the wave model, but is dominated by the wind generated loading.



The Walney Offshore Wind (WOW) Project

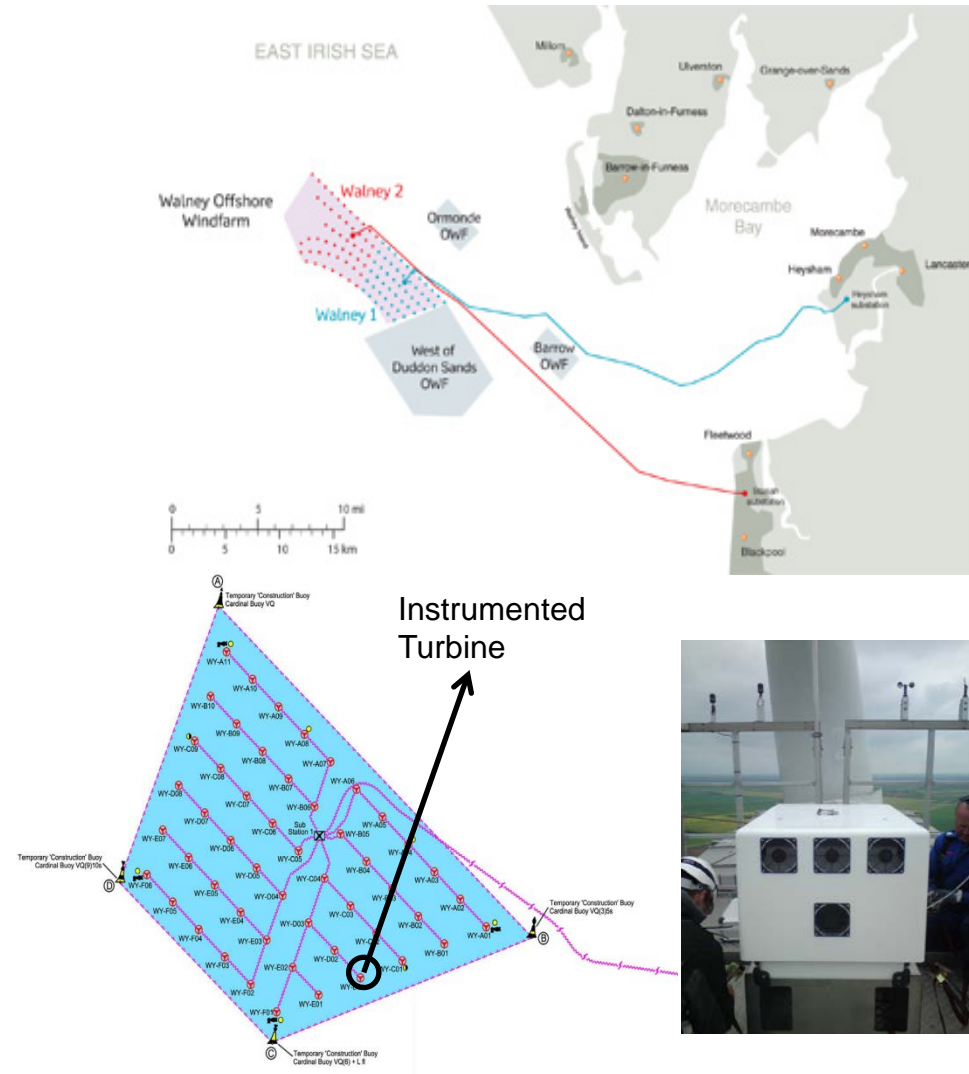
- Comprehensive loads validation on a state of the art 3.6MW wind turbine
- Collaboration with Siemens Wind Energy and DONG energy

Key Measurements

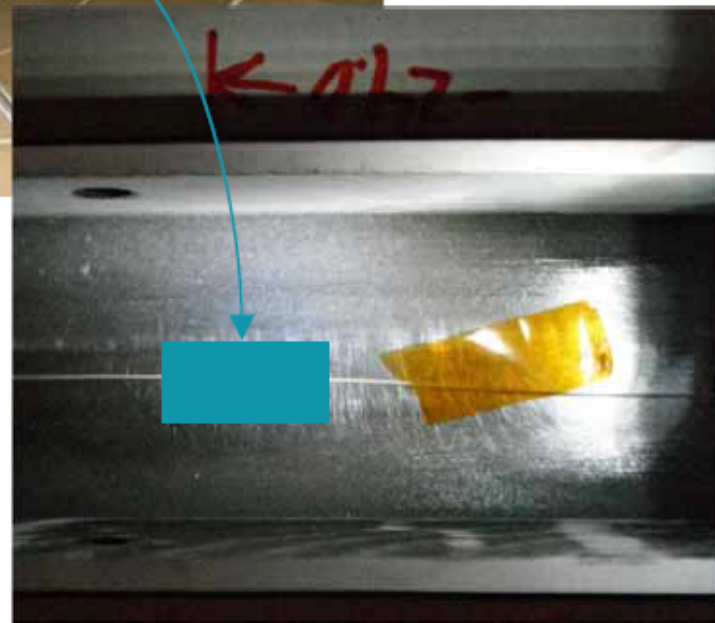
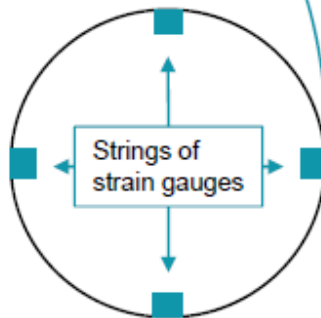
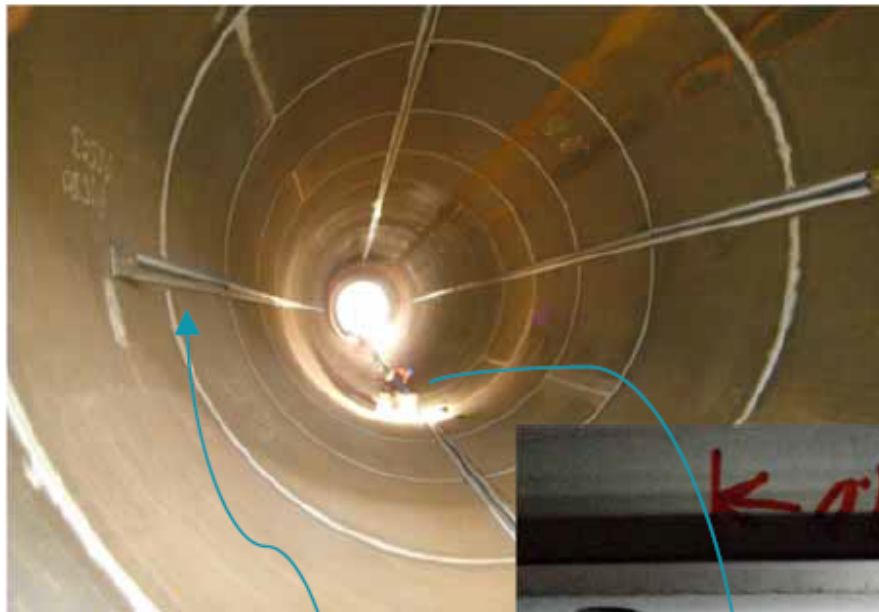
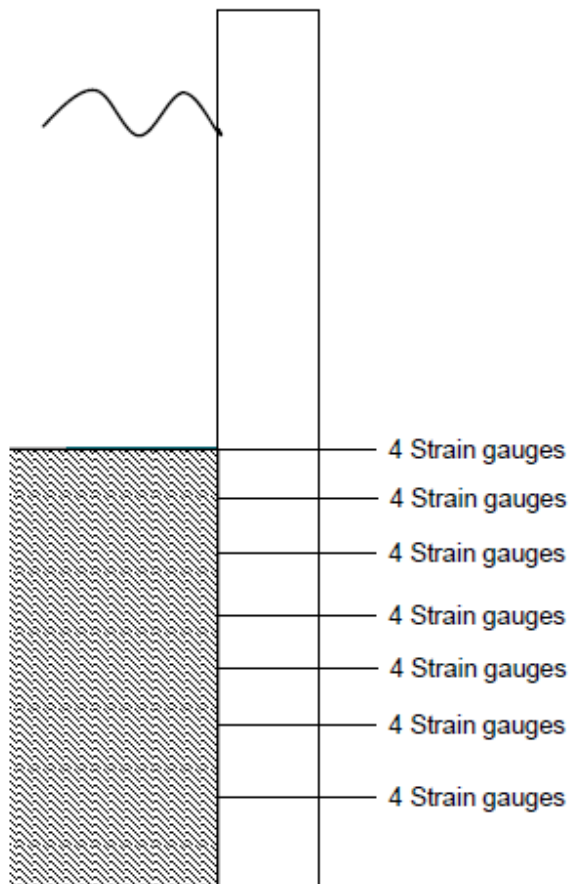
- Nacelle mounted LIDAR for wind measurements
- Wave sonar and Buoy at turbine
- Accelerometers, strain gauges on
- Blade root, drive train, tower and foundation

Scientific Objectives

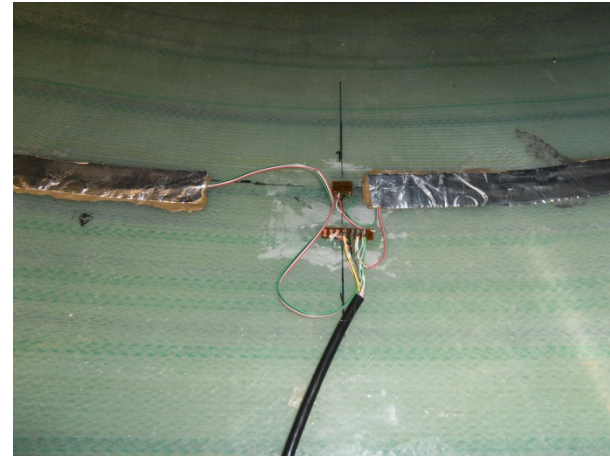
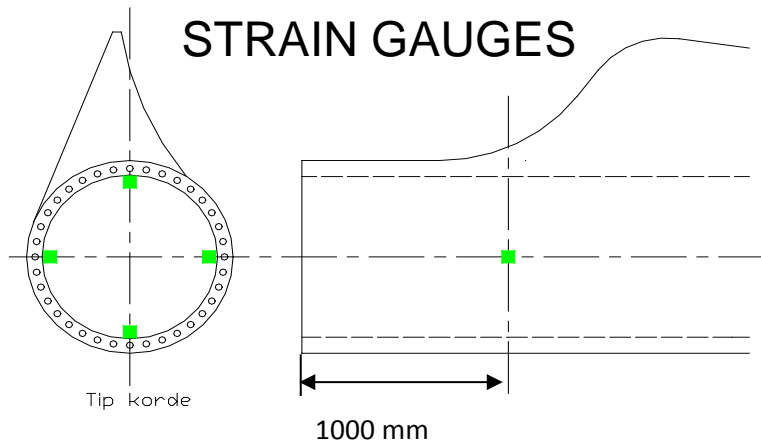
- Validation of the dependencies of design loads
- Prediction of turbine net damping
- Advanced wind/wave correlation studies
- Wake effects on loads



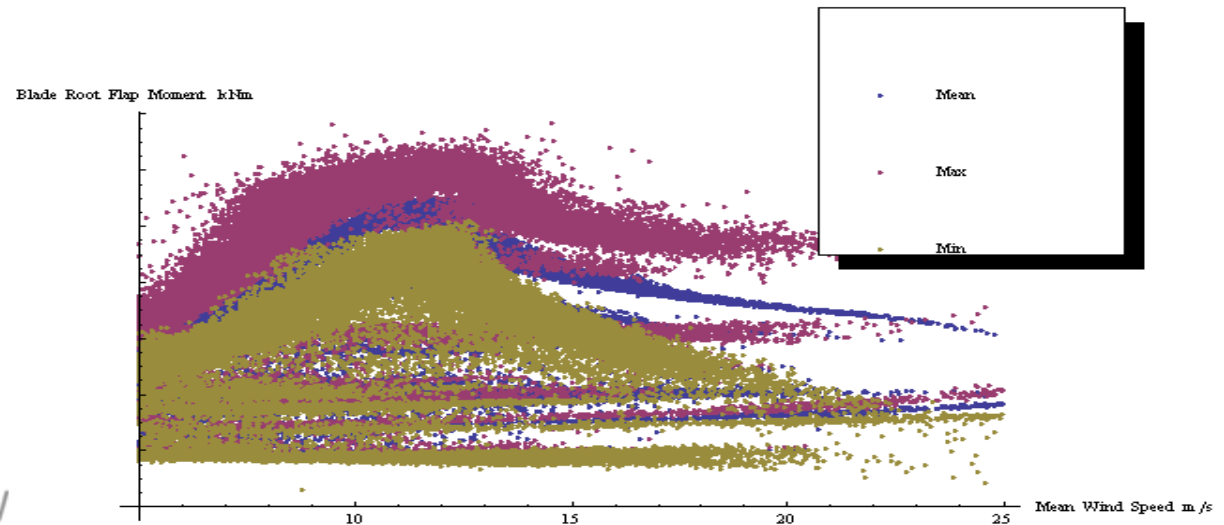
Monopile Loads Validation



Blade Loads Measurements



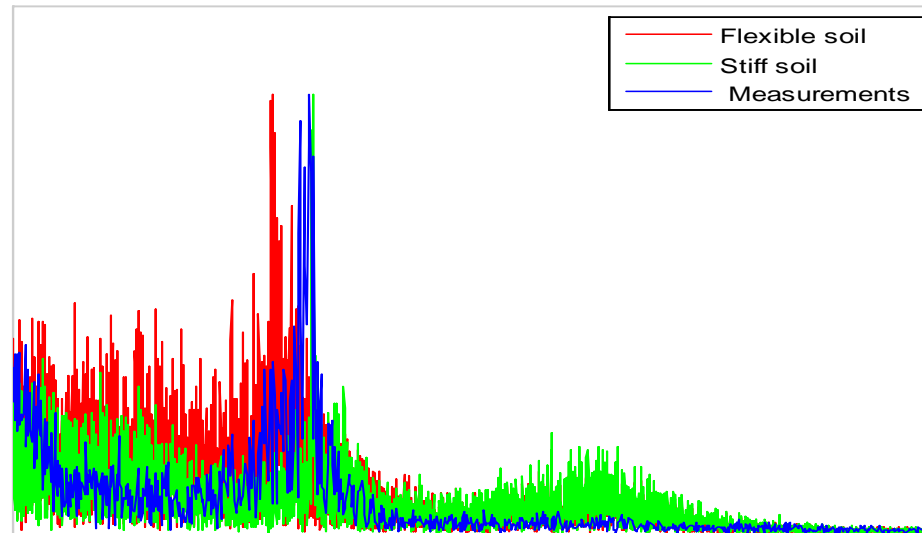
- Blade Root Flap and Edge moments on all 3 blades



Effect of Soil Flexibility

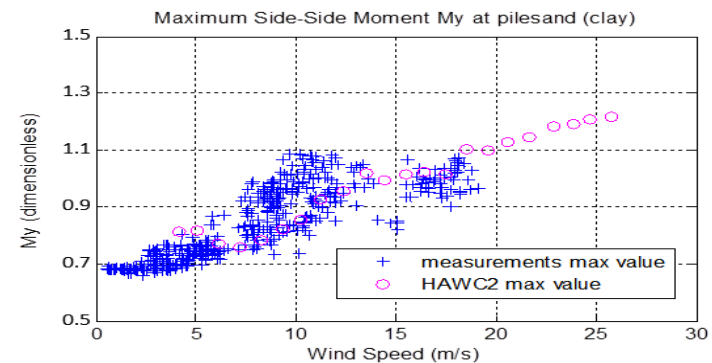
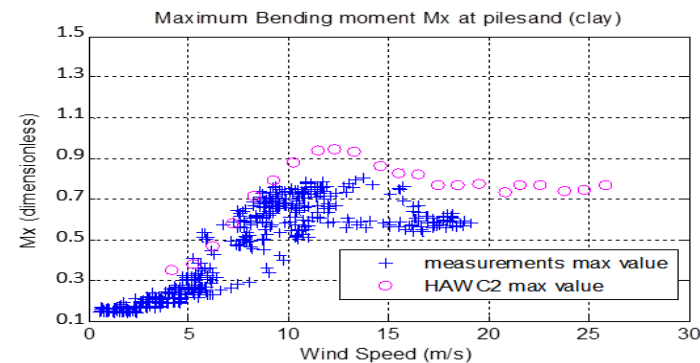
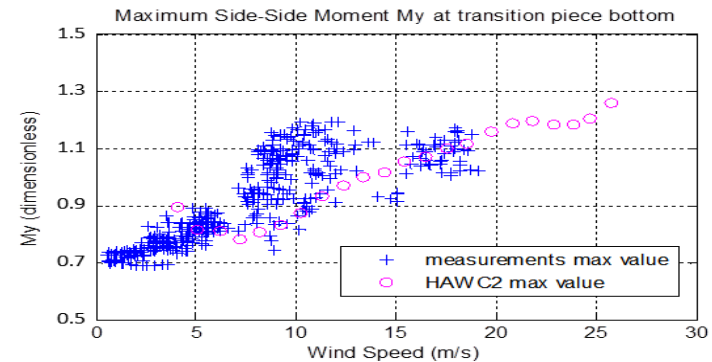
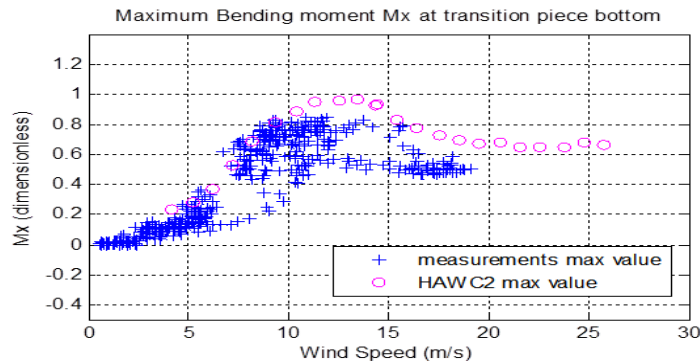
1. The measured soil properties at a point on the Walney site were used to develop P-Y curves as per the DNV model for nonlinear soil springs.
2. However the frequency response from the measured monopile strains at the soil surface showed that the natural frequencies did not correspond to the modeled soil conditions, but rather with a more rigid soil condition.

FFT analysis on M_x at transition piece bot



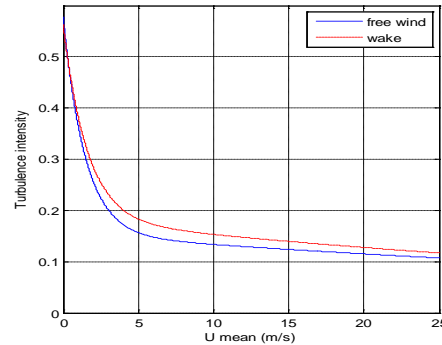
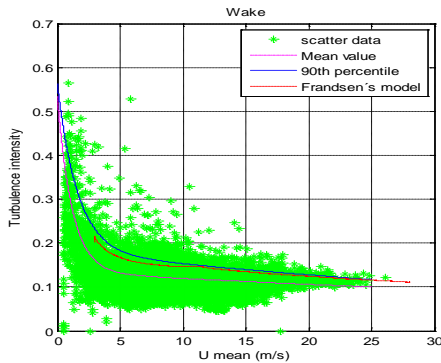
Comparison of Peak Loads

- DLC 1.1 simulations were run in HAWC2 based on wind measurements from the Nacelle Anemometer (since nacelle based LIDAR was not yet installed)
- The comparisons are normalized with the maximum from the simulations.

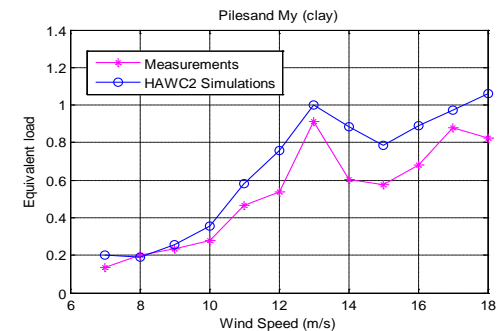
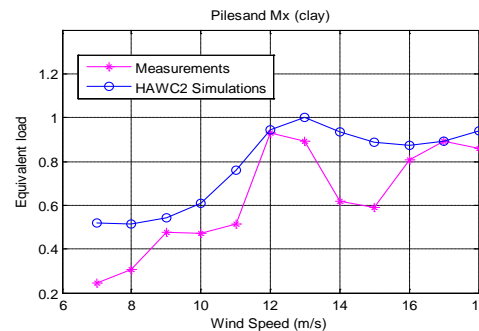
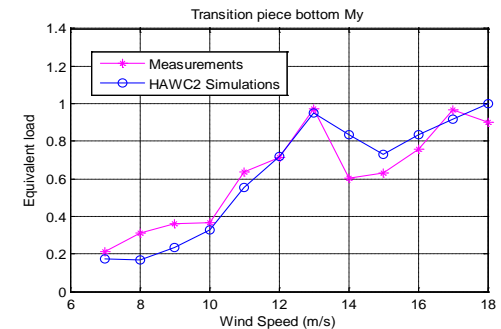
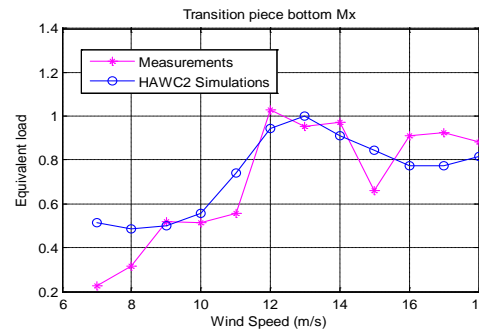


Comparison of Fatigue Loads in Wakes

The wake effects are computed using the Sten Frandsen model



1. The 1HZ damage equivalent loads from simulation and measurement show similar trends.
2. Differences between simulation and measurement increase near the soil surface.



Fully Coupled Versus Decoupled Simulations



- Uncoupled simulation : The wind turbine jacket base loading from hydrodynamics is computed separately using Abaqus and added to the loading from the rotor at each time step.
- Fully coupled simulation: The jacket and wave kinematics is directly integrated into HAWC2 and the turbine dynamics is computed simultaneously with the marine loading.
- The uncoupled simulation allows study of different support structural concepts and optimization without integrating the wind turbine in the design loop.
- A comparison of DLC 1.1 loads time series at the Jacket legs is performed to assess the error introduced by decoupled simulations.

Modal Comparison

Table 1: Natural frequencies of the jacket structures

Mode	Abaqus model	HAWC2 model
1 st Fore-Aft Mode	0.3167 Hz	0.3164 Hz
1 nd Side-Side Mode	0.3172 Hz	0.3214 Hz
2 st Fore-Aft Mode	1.2030 Hz	1.2047 Hz
2 nd Side-Side Mode	1.2085 Hz	1.2144 Hz



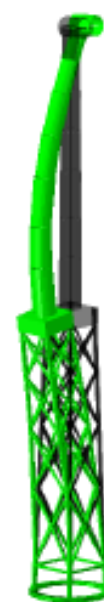
(a) 1st Fore-Aft Mode



(b) 1nd Side-Side Mode

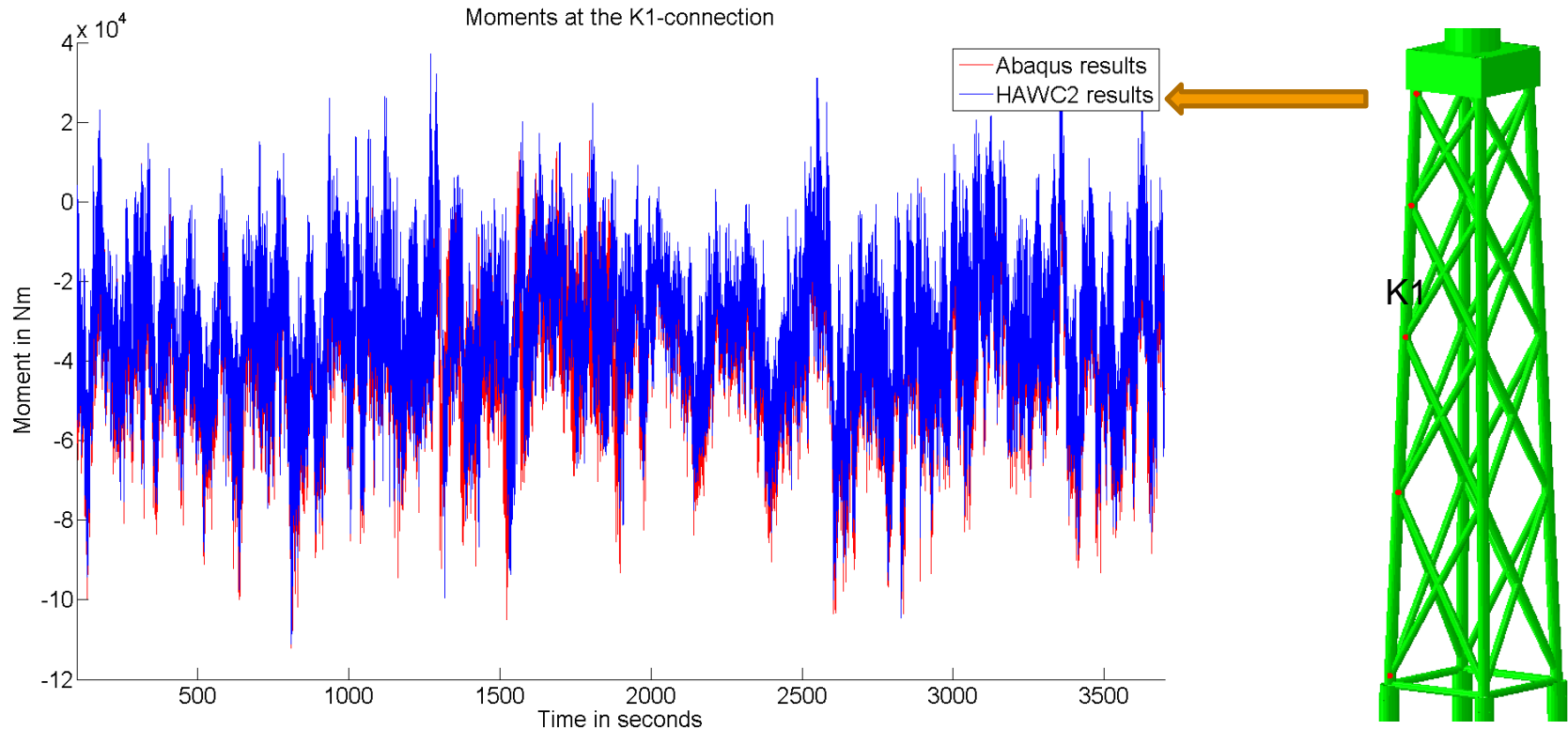


(c) 2st Fore-Aft Mode



(d) 2nd Side-Side Mode

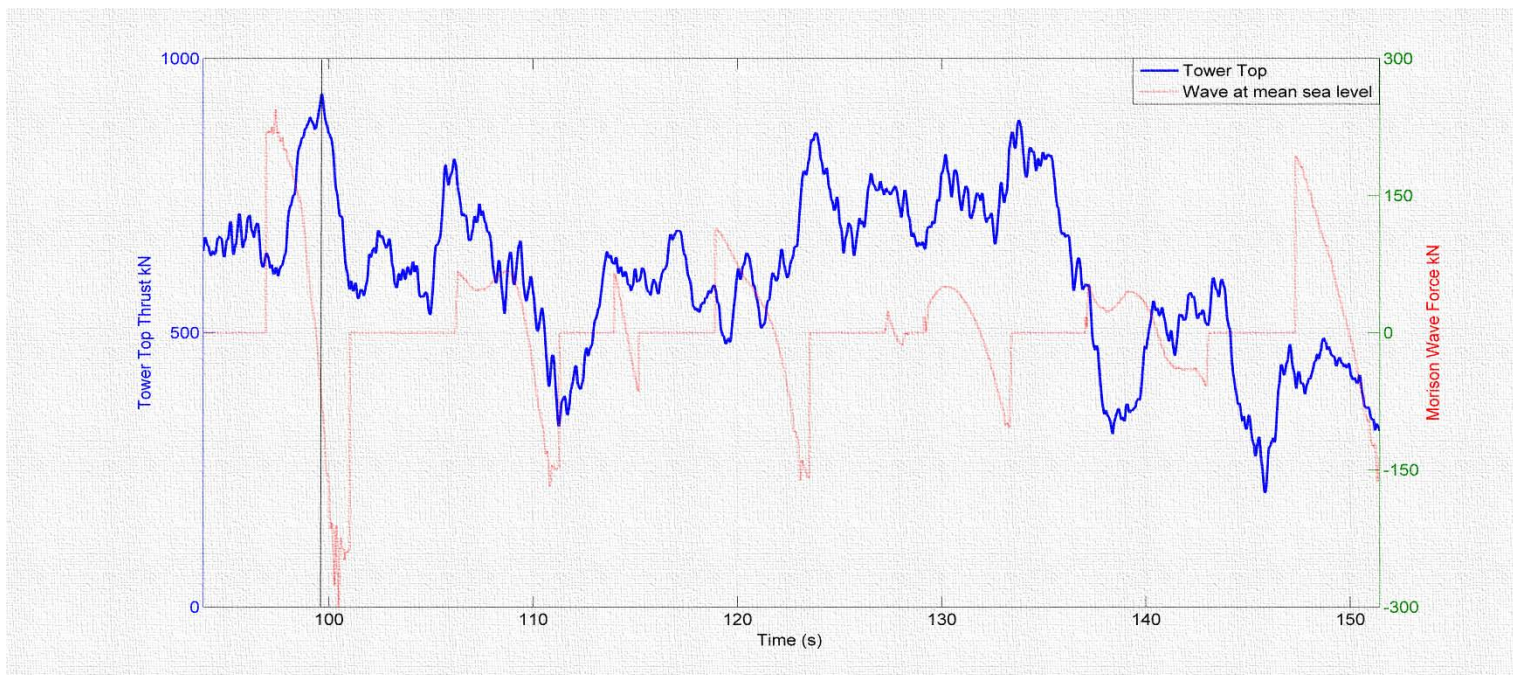
Coupled Versus De-Coupled Loads



Difference in the amplitudes of the over turning moments is of the order of 20% between coupled and uncoupled time series.

Wind/Wave Phase relationship

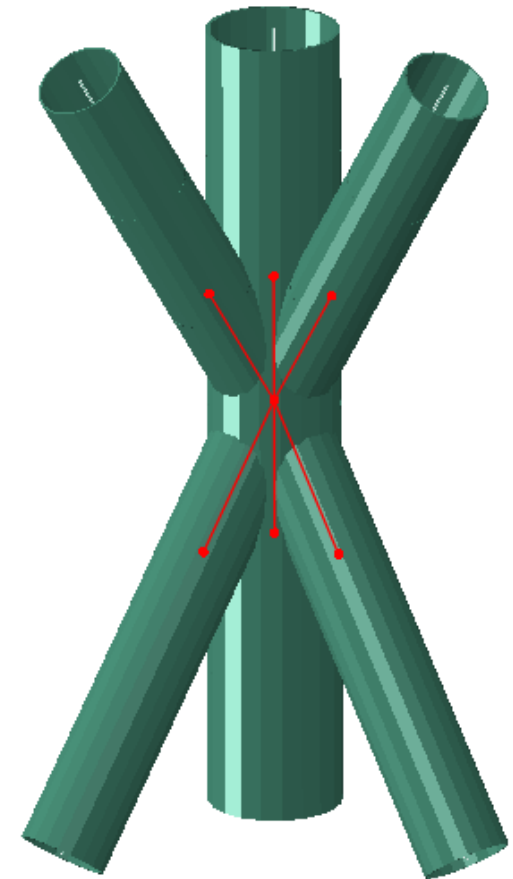
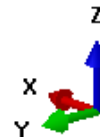
- The rotor loads and the wave forces are usually not in phase in fully coupled simulations, which implies that their respective peaks do not add up.
- This implies that fully coupled simulations over few 10 minute durations provide a lower extreme sub structure design load as compared to uncoupled simulations where the rotor loads are directly added to the hydrodynamic loads.



Jacket Design – Welded Joints

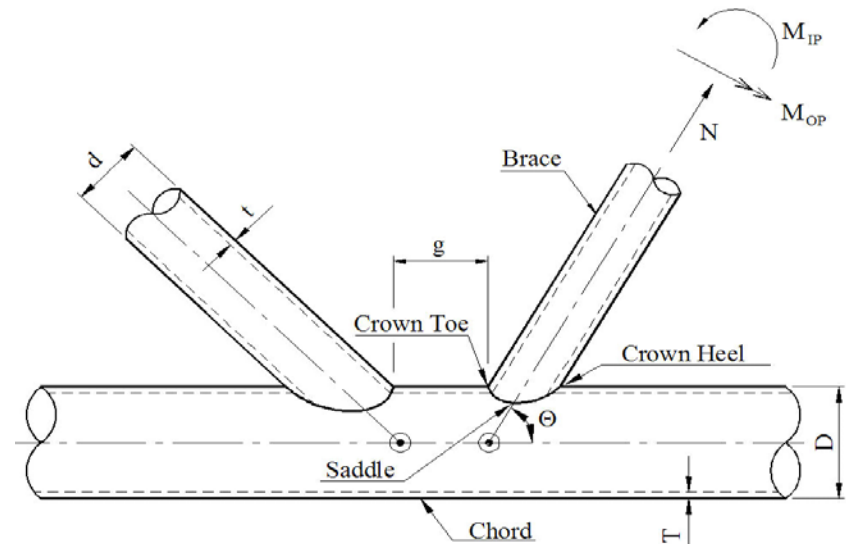
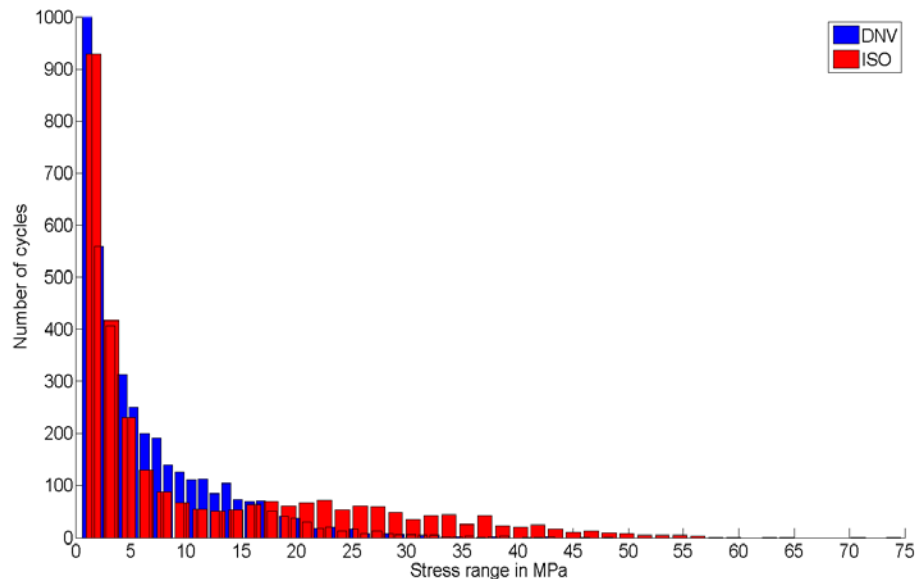
- The "Hot Spot" regions at welded joints need to be carefully designed by considering all 6 components of loads at the welded joint.
- According to the DNV-RP-C203 , the hot spot stress should be evaluated at 8 spots around the circumference of the intersection.
- Also referred to is the ISO 19902 standard, where the weld hot-spots should both be considered at the chord side and at the brace side of the weld.
- Fatigue Design :

$$N = \begin{cases} K_1 \Delta \sigma^{-m_1} & \text{for } \Delta \sigma \geq \Delta \sigma_c \\ K_2 \Delta \sigma^{-m_2} & \text{for } \Delta \sigma < \Delta \sigma_c \end{cases}$$



Jacket Design – Welded Joints

- The method used in ISO 19902 estimated a lower number of cycles than the method used in DNV. However, the stress range estimated using ISO 19902 are higher for which reason larger fatigue damage is estimated.



- The DNV approach considers 8 hot-spots around each chord/brace intersection whereas the ISO approach only considers 4. Four hot-spots were found to be sufficient to determine the reliability level.

Mean Load Effects on Fatigue Life

Methods to obtain a mean corrected amplitude

–**Goodman (GDM)**: simple but conservative (Downing et al (2009))

$$M_{ar} = \frac{M_a}{1 - \frac{M_m}{M_u}}$$

–**Walker (WLK)**: good for relatively low mean values (Downing et al (2009), Lee et al (2005)).

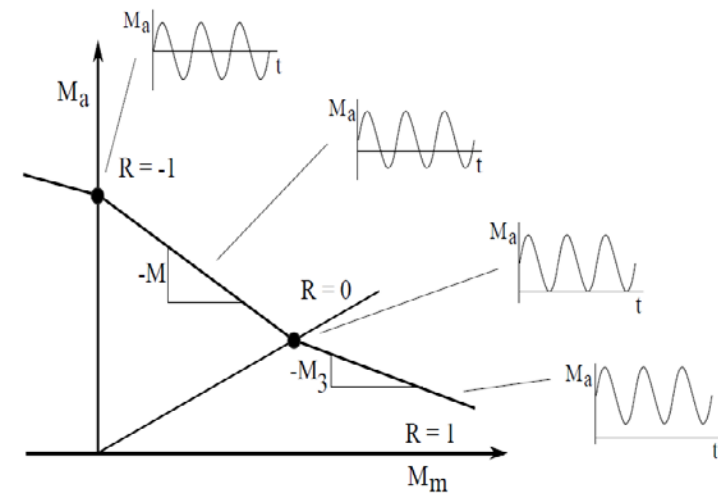
$$M_{ar} = M_a \left(\frac{2}{1 - R} \right)^{1-\gamma}$$

$$\gamma = -0.0002\sigma_u + 0.8818$$

–**Mean moment sensitivity factor (MSF)**: alternative for large mean values (Lee et al (2005)).

$$M_{ar} = M_a + m_f |M_m|$$

$$m_f = 0.00035\sigma_u - 0.1$$

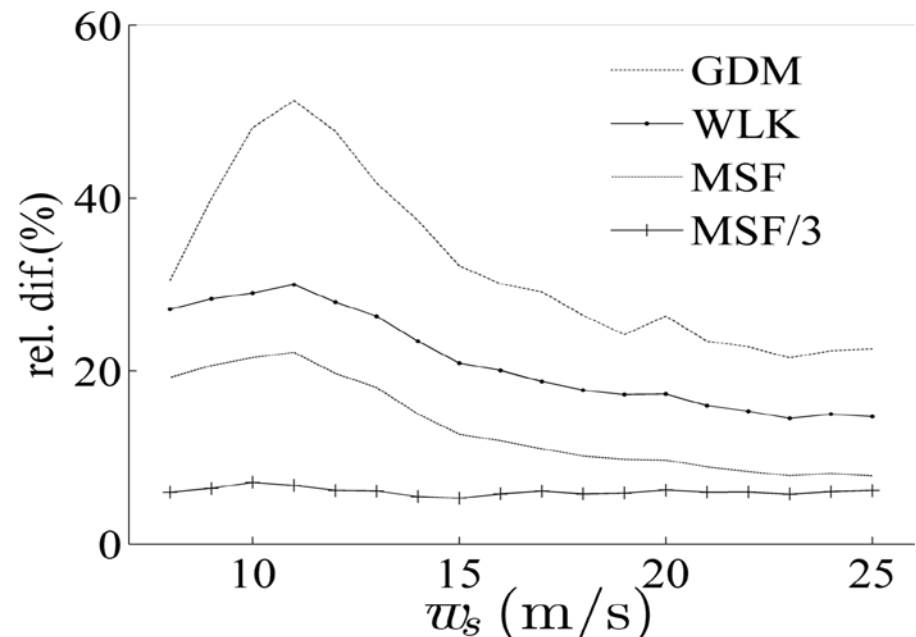
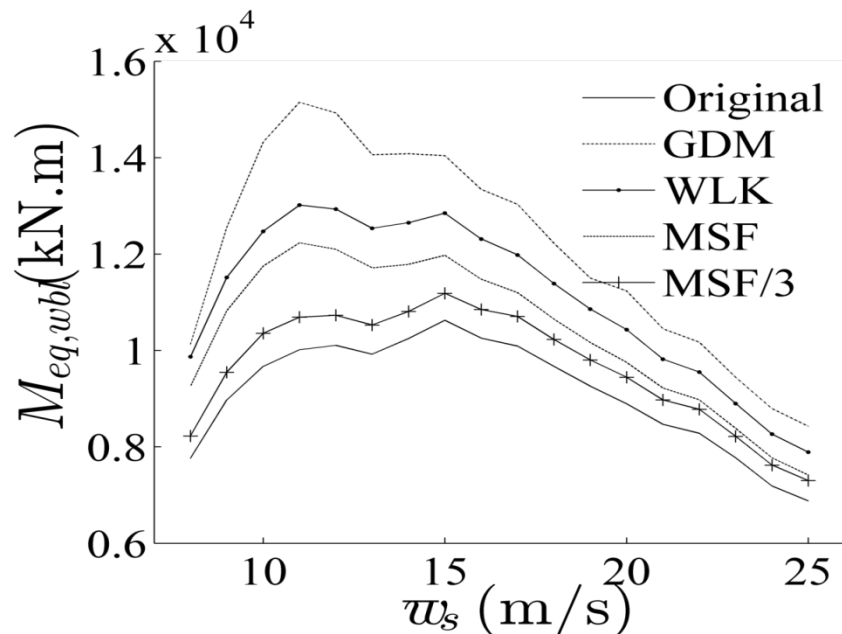


Mean Load Corrections Adopted in Wind Turbine Design Standards

- DNV Recommended Practice DNV-RP-C203, "Fatigue Design of Offshore Steel Structures" states that "It is only necessary to consider the ranges of the cyclic stresses in determining fatigue endurance"
- The DNV standard also points out large uncertainties in fatigue life estimation and therefore refers to the design S-N curve being 2 standard deviations below the mean S-N curve to failure.
- The GL Guideline for the certification of wind turbines Edition 2010 states that "Material's fatigue strength is sensitive to mean stresses and the influence of the mean stress is to be considered by means of the Haigh diagram"
- Therefore there are two methods to employ mean correction, 1) A mean shifted S-N curve or 2) Mean Stress corrected amplitude
- Since the S-N curve is often uncertain, the mean stress corrected method may be preferable

Effect of Mean Corrections

- The mud level overturning fatigue moment is computed using the R-corrected mean sensitivity factor (MSF/3), mean sensitivity factor (MSF), Walker (WLK), and Goodman (GDM) techniques.
- The methods give increasingly conservative results and the mean corrected results are greater than without using mean correction.



SUMMARY

- The overall aeroservoelastic load predictions on the sub structure seems to agree with load measurements.
- Uncoupled loads simulation with irregular nonlinear waves can provide a conservative design load on the foundation as compared with fully coupled simulations.
- Fatigue load predictions have a large uncertainty due to the effect of varying mean load and due to welded joints.
- The effect of wind/wave misalignment combined with uncertain soil flexibility is a major uncertainty in both fatigue and extreme load estimation.

Acknowledgments

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and also

- A part of the work in the **Danish EUDP** project titled, “**Offshore wind turbine reliability through complete loads measurements**”, project no. 64010-0123.
- The financial support from both projects is greatly appreciated.